PROBABILISTIC SEISMIC HAZARD ANALYSIS FOR NUCLEAR POWER PLANTS – CURRENT PRACTICE FROM A EUROPEAN PERSPECTIVE

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The paper discusses the methodology and the use of probabilistic seismic hazard analysis (PSHA) for nuclear power plants from a European perspective. The increasing importance of risk-informed approaches in the nuclear oversight process observed in many countries has contributed to increasing attention to PSHA methods. Nevertheless significant differences with respect to the methodology of PSHA are observed in Europe. The paper gives an overview on actual projects and discusses the differences in the PSHA-methodology applied in different European countries. These differences are largely related to different approaches used for the treatment of uncertainties and to the use of experts. The development of a probabilistic scenario-based approach is identified as a meaningful alternative to the development of uniform hazard spectra or uniform confidence spectra.

KEYWORDS : Probabilistic Seismic Hazard Analysis, Uncertainty Analysis, Scenario-based Seismic Risk Analysis

1. INTRODUCTION

Since the development of Cornell's engineering approach to seismic risk analysis (Cornell, 1968) the probabilistic approach to seismic hazard analysis gradually developed into a meaningful alternative to traditional deterministic seismic hazard analysis. Different probabilistic approaches have emerged (Klügel, 2008) and found their application in different fields of engineering. The increasing importance of risk-informed approaches in the nuclear oversight process observed in many countries has contributed to increasing attention to probabilistic seismic hazard analysis methods. Nevertheless, some significant differences with respect to the methodology of probabilistic seismic hazard analysis remain. These differences lead to significantly diverging results of seismic Probabilistic Risk Assessments (PRA). These differences are amplified by the large uncertainties associated with the prediction of earthquake occurrence especially in low to moderate seismic regions as is characteristic for Central and Northern Europe. This paper provides a European perspective on the use of Probabilistic Seismic Hazard Analysis for Nuclear Power Plants, discussing its use for different applications, highlighting differences in the methods used, the shortcomings of some of the established methods as well as some new developments.

2. SUMMARY DESCRIPTION OF THE METHODOLOGY OF TRADITIONAL PSHA

The acronym traditional PSHA is used here to differentiate between the approach developed by Cornell (1968) and expanded by McGuire (1976) providing the required software support and some of the alternate approaches discussed below. The current state of the development of traditional PSHA methodology is manifested in the SSHAC methodology popular in the USA that to some extent was exported to Europe. Therefore, the traditional PSHA approach including SSHAC methodology (SSHAC, 1997) provides the basis for the description of the methodology in this chapter. The basic methodology of PSHA is illustrated in figure 1 taken from Klügel (Klügel, 2008). The workflow consists of five steps.

Step 1 is dedicated to the definition of earthquake sources. Here, the available information on the geological and seismo-tectonic features of the region of interest, including information from the available earthquake catalogs, is used to provide a characterization of the seismic sources of the region. This step usually ends in the development of a seismo-tectonic model of the region and a seismic zonation model.

Step 2 is the definition of seismicity recurrence characteristics for each source. The SSHAC model (SSHAC,

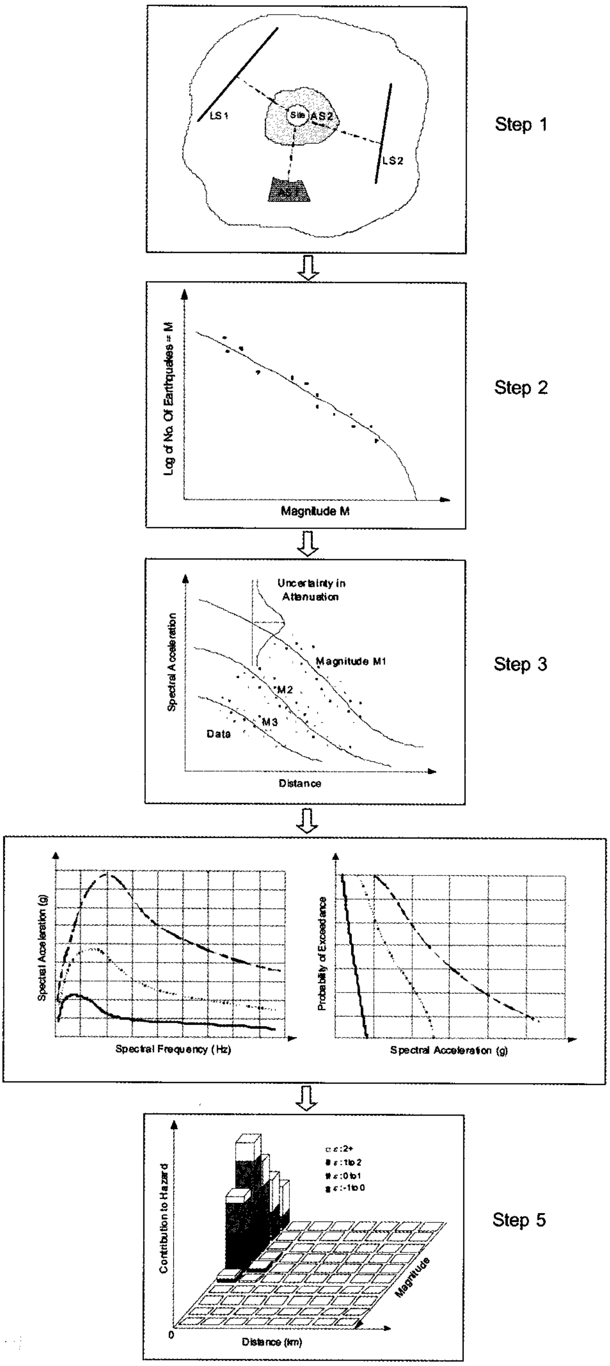

Fig. 1. Workflow for a Modern PSHA Study Following the Traditional PSHA Approach (Taken from Klügel (2008))

1997) prefers the use of the exponentially truncated Gutenberg-Richter relation, although other models can be used, too. Recently, Brownian Passage Time (BPT) models, that are based on the inverse Gaussian distribution model, became a meaningful alternative, especially in areas characterized by pronounced seismogenic features (large crustal faults or plate boundary areas).

Step 3 comprises the development of a ground motion prediction model, including the treatment of ground motion variability. The use of empirical ground motion prediction equations still represents the mainstream approach due to its seemingly simplicity.

Step 4 includes the development of uniform hazard spectra for different probabilities of exceedance and the development of hazard curves. Usually traditional PSHA stops at this point (Reiter, 1990). It is believed that the uniform hazard spectrum expressed in terms of spectral accelerations represents a uniform hazard occurring with the same frequency of occurrence for all relevant spectral frequencies, thus enveloping all possible earthquake scenarios. It will be shown in section 6 that this belief is not justified. It is worth mentioning that in Europe an alternate approach to the traditional PSHA approach is (still) popular (in Germany and Russia) which is based on the calculation of unified confidence hazard spectra.

Step 5 involves the disaggregation of the hazard to develop controlling scenario events defined by magnitude distance pairs. Modern PSHA studies include this step to gain a better physical representation of the hazard in terms of earthquakes controlling the seismic hazard at a given site. Usually controlling earthquakes are expressed in terms of magnitude-distance pairs. This information is helpful for later engineering evaluations. For example for a dynamic non-linear analysis of a structure it is necessary to generate several sets of time-histories that should match the uniform hazard spectrum (or disaggregated spectra) simultaneously representing the characteristic of the seismic sources governing the seismic hazard at the site of interest. The information obtained from the disaggregation can also be used for more detailed investigations based on finite-fault simulations. Such simulations can be helpful to evaluate maximum ground motion limits, especially from near-site sources. The information obtained can be incorporated into the PSHA procedure in an iterative manner providing improved estimates of the upper ground motion limit feasible for a given site used for the truncation of the hazard integral. This incorporation would require an additional hazard quantification step repeating steps 4 and 5 of the workflow, if necessary several times.

A characteristic for the traditional PSHA approach is that it evaluates a uniform seismic hazard spectrum and the hazard curves corresponding to it with the help of the following simple mathematical model, generalized from Reiter (Reiter, 1990):

$$E(a)=\sum_{i=1}^{N} v_i \int_{m_0}^{m_u} \int_{r=0}^{\infty} f_i(m) f_i(r) P_i(S_a > a|m,r)\,dr\,dm \qquad (1)$$

Where $E(a)$ is the expected number of exceedances (the mean annual rate) of ground motion level a during a specified time period t, v_i is the mean rate of occurrence of earthquakes between lower and upper bound magnitudes (m_0 and m_u) being considered i the ith source, $f_i(m)$ is the probability density distribution of magnitude (recurrence relationship) within source i, $f_i(r)$ is the probability density distribution of epicentral (or source) distance between the various locations within source i and the site for which the hazard is being estimated and $P_i(S_a > a|m,r)$ is the probability that a given earthquake of magnitude m and epicentral distance r located in the seismic source i will exceed ground motion level a. It is worth mentioning that eq. (1) can be used for any type of intensity characteristic of ground motions. Indeed the direct use of intensities (in the new European scale EMS-98) is very popular, especially in Germany.

The model described is based on the assumption that the frequency distributions of temporal and spatial occurrences of earthquakes can be treated as statistically independent variables. This simplification is partially corrected by the consideration of a set of different sources with different temporal distributions (recurrence relationships) and different spatial characteristics of epicenter locations (spatial distribution) and by considering source-dependent ground motion prediction equations (GMPE) while evaluating the probability of exceedance of ground motion level a. In practice, several additional simplifications and modifications are applied, which move the model represented by eq.1 further away from the reality of earthquake occurrences. Following Cornell (1968) it is usually assumed that the observations of earthquakes at a given site follow a Poissonian arrival process eliminating the temporal dependence completely.

For area sources (these are areas without exact identification of seismogenic sources, therefore seismicity is described as diffuse) usually a uniform probability density distribution for earthquake location is applied. It is believed that this type of non-informative probability distribution adequately reflects the "lack of knowledge" associated with the characterization of diffuse seismicity. Some approaches (PEGASOS, Abrahamson et al, 2004) do not rely on a uniform distribution of earthquake epicenters (locations) within a given source but treat each point within an area source as a starting point of a fault rupture with a length defined by a magnitude-length scaling relationship (Klügel et al, 2006). Additionally, a uniform probability density distribution is assumed with respect to the directions which the rupturing faults may take. It is worth noting that this approach is not at all a non-informative probabilistic approach. It introduces a systematic (intended) bias towards the overestimation of the importance of near-site earthquakes due to the parallel use of simple amplitude-decay attenuation relations used for the calculation of the probability of exceedance P.

An additional simplification of the method consists in neglecting the source dependency of ground motion prediction models by replacing them either by a regional model or a logic tree model weighting different model alternatives as a replacement for a regionally validated ground motion prediction model. The use of logic trees has become a standard technique in the traditional PSHA method (SSAC, 1997). It is used as a means to capture potential epistemic uncertainties by weighting equally relevant alternate ground motion prediction models. It is worth mentioning that it is nearly impossible for a weighted logic tree model to assure a better performance in comparison with regional earthquake recordings because this is applicable only for a set of very specific weights. This can be shown easily. A logic tree ground motion prediction model can be presented as a weighted model by the following equation:

$$g(m,r) = \sum_{i=1}^{n} w_i h_i(m,r) \tag{2}$$

Let the regional model be $k(m,r)$. To assure that the weighted logic tree model in eq. (2) performs better than the regional model developed on the same set of data (if it is a validated model) we have to require that the least square error associated with the prediction of the recorded data points by the weighted logic tree model $g(m,r)$ should be smaller than for the regional model. Therefore we have to require:

$$L^2\left[g(m,r)\right] \le L^2\left[k(m,r)\right] \tag{3}$$

Where $L^2[\cdot]$ is the least square error calculated for the prediction of regional data sets by the different models $g(m,r)$ and $k(m,r)$. Returning to eq. (2) it is obvious that compliance with this relationship can only be expected for sets of very specific weights. In PSHA it is usually not analyzed whether the resulting weighted logic tree model really "outperforms" existing regional attenuation relationships. It is worth mentioning that even the use of a regional attenuation model in a PSHA leads to a loss of information on source characteristics, losing the link between the PSHA model and the available information contained in the seismological, geotechnical and geological database. Usually the information on focal mechanisms, on directivity effects (a result of preferred stress regimes for the sources in the region) and on topographical specifics is lost.

Another difference in the use of the PSHA method in different countries of Europe and in comparison to its use in the SSHAC method consists in the calculation of the probability of exceedance $P_i(S_a > a|m,r)$. The basis for the calculation of this probability is usually an empirical ground motion model of the type:

$$\ln(S_a) = g(m,r,X_{other}) + \varepsilon\sigma \qquad (4)$$

where X_{other} represents a vector of explanatory variables other than just magnitude m and distance r;σ represents the standard error resulting from the development of the ground motion prediction equation by regression. Together with the parameter ε it defines the different confidence intervals for eq. (4). Setting the parameter ε correspondingly, confidence intervals which correspond to different probability values with which the computed confidence interval would include the true value of ground motion acceleration $S_{a,true}$ can be computed as shown in eq. (5)

$$S_{a,tru} = (S_a - \varepsilon\sigma, S_a + \varepsilon\sigma) \qquad (5)$$

The consideration of confidence intervals in PSHA is equivalent to including the epistemic uncertainty associated with the evaluation of the true spectral acceleration by eq. (4) into the analysis.

The SSHAC approach (SSHAC, 1997) ignores the origin of the term $\varepsilon\sigma$ as a characteristic of the confidence intervals in eq. (4) and interprets σ as aleatory variability. Therefore, the SSHAC approach converts the "epistemic uncertainty characteristic σ" representing "lack of knowledge" into an inherent random property of seismic ground motion (see section 4 for the definitions). It is worth mentioning that there is absolutely no basis for this conversion (it simply contradicts the laws of mathematical regression) although it has become mainstream practice in traditional PSHA, except in some European countries (Germany and Russia).

Depending on how the regression error term in eq. (4) is interpreted, different models for the computation of the probability of exceedance $P_i(S_a > a|m,r)$ are used in the different PSHA approaches.

Traditional PSHA (eq. (1)) calculates the probability of exceedance as:

$$P_i(S_a > a|m,r) = \Phi'\left(\frac{\ln S_a - g(m,r,X_{other})}{\sigma}\right) \qquad (6)$$

while the second approach does not calculate an expected value (mean) of the combined aleatory-epistemic uncertainty distribution (this is the meaning of equation (1) according to the SSHAC approach (SSHAC, 1997)) but evaluates a seismic hazard corresponding to different confidence levels ε in eq. (4) (unified confidence spectra):

$$P_i(S_a > a|m,r,\varepsilon) = H\left[g(m,r,X_{other}|\varepsilon) - \ln a\right] \qquad (7)$$

here $H[\cdot]$ is the Heaviside "jump" function taking the value 1 if its argument is larger than 0 and the value 0 if its argument is smaller or equal 0. The value of ε defines the confidence level. For the purpose of design applications, usually a value of $\varepsilon = 1$ is applied defining the seismic hazard consistently at the $+1\sigma$ confidence level.

It is worth mentioning that the results of a PSHA evaluating uniform hazard spectra and the results of a PSHA expressed by uniform confidence level are very different. The two approaches differ in the definition of key terms as well as in the treatment of uncertainties.

3. APPLICATIONS OF PSHA FOR THE DESIGN AND THE PROBABILISTIC RISK ASSESSMENT OF NUCLEAR POWER PLANTS IN EUROPEAN COUNTRIES

Internationally, PSHA is used both for the development of the seismic design basis of nuclear power plants as well as for probabilistic risk assessments (PRA). The turning point for the acceptance of PSHA as a tool for the development of the seismic design basis can be seen in the decision of the US NRC to use PSHA and seismic risk analysis (seismic PRA) to justify and to approve the construction and operation of the nuclear power plant at the Diablo Canyon site in California. The Diablo Canyon plant had already been under construction when the Hosgri fault, offshore from the site at about 5 kilometers distance, was discovered. The failure to discover this fault (which has the capacity of causing a magnitude M7+ earthquake) by the traditional deterministic method (in the understanding of the then valid NRC regulations, not in the understanding of earth sciences) was rooted to the deterministic method itself (it should have been rooted to the then valid NRC regulation neglecting the importance of offshore investigations, not to the deterministic method in general). The PSHA method based on an evaluation of all possible seismic sources estimating their seismic activity by probabilistic models (usually the Gutenberg-Richter model) seemed to provide some advantage. In the meantime PSHA has become the one and only tool for the development of the seismic design basis of new nuclear power plants in the USA (NRC RG 1.165). The IAEA decided to move along a different way. The current Safety Guide (IAEA NS-G-3.3) for the evaluation of seismic hazards as well as the Safety Guide (IAEA NS-G-2.13) for the evaluation of seismic safety allow for the use of deterministic and probabilistic approaches for the development of the seismic design basis of nuclear power plants. Both guides also allow for the use of different probabilistic approaches eliminating the preference of simple probabilistic models like the Gutenberg-Richter model for earthquake occurrence characteristics for the US NRC recommendations on PSHA (SSHAC, 1997). In European practice (in "nuclear" countries France and Germany which have developed a nuclear industry) PSHA is not used as the sole method for the development of the seismic design basis of new nuclear power plants. In general the deterministic method is preferred for design applications while probabilistic approaches are used to check the results of a deterministic analysis. This check is regarded as meaningful to ensure compliance with the IAEA requirement that sufficiently rare earthquake events have to be selected as the design basis for nuclear power plants.

A special situation exists in Switzerland. Traditionally, Swiss regulators closely follow the methods and approaches in use or recommended by the US NRC. This is one of the reasons why the PEGASOS study (see section 5), one of the trial applications of the SSHAC method for nuclear power plants was launched in Switzerland and funded by Swiss nuclear power plants. Nevertheless, there is still no regulation on how to develop the seismic design basis for new nuclear power plants.

The situation is different with respect to probabilistic risk assessment. Here, the use of probabilistic methods is unavoidable to provide the input required for a seismic PRA. Nevertheless, some significant differences exist with respect to the PSHA methodology in use (see sections 2 and 6). Some of the most important differences relate to how uncertainty is treated in different methods and to what extent expert knowledge is utilized to derive quantitative seismic hazard results.

4. UNCERTAINTY ANALYSIS AND EXPERT JUDGMENT

As mentioned, a key difference between the different PSHA methods lies in the area of the definition of key terms of uncertainty and their treatment. An understanding of the nature of uncertainties and how they have to be propagated in mathematical models is necessary for any analyst attempting to develop quantitative risk or hazard models. Uncertainty in general is used as a term to express our lack of knowledge of the future behavior of systems (models of real world systems) with respect to attributes of interest. So in general, all uncertainty is epistemic *by its nature of origin*.

The most important relevant classification system for traditional PSHA consists in the separation between epistemic uncertainty and aleatory variability (uncertainty). In system science, epistemic uncertainty represents the lack of knowledge uncertainty associated with the definition of a suitable model making it possible to represent the behavior of a system with respect to the attributes of interest. This can be regarded as a definition of epistemic uncertainty in the narrow sense. Aleatory variability (uncertainty) was defined originally simply as *variation of quantities in a population*. The definition of aleatory uncertainty (variability) was refined and expanded in system science (Ayyub and Klir, 2006, pp. 57/58):

"Inherent randomness (i.e., aleatory uncertainty): Some events and modeling variables are perceived to be inherently random and are treated to be non-deterministic in nature. The uncertainty in this case is attributed to the physical world because it cannot be reduced or eliminated by enhancing the underlying knowledge base. This type of uncertainty is sometimes referred to as aleatory uncertainty. An example of this uncertainty type is strength properties such as steel and concrete, and structural load characteristics such as wave loads on an offshore platform."

This expansion of the definition is unfortunately ambiguous, as the obvious contradiction between the terms "inherent randomness" (measurable statistically) and "perceived" (subjective interpretation by an analyst) indicates. Either an analyst deals with the inherent properties of the real world or with the perception of persons expressed by their views of the world. It would not be a big issue if this concept had not found its way into engineering science as a baseline model for probabilistic analysis using a "combined, joint" probability model (Ayyub and Klir, 2006):

$$P = \bar{P}\hat{P} \tag{8}$$

Here P is a random variable representing both uncertainty types, i.e. the combined uncertainty; $\bar{P}$ is a random variable representing the aleatory variability and $\hat{P}$ represents the epistemic uncertainty.

This approach, which dates back to Ang (1970) and Ang and Tang (1975, 1984) is very problematic. First of all it combines two different approaches to the theory of probability: the frequentist approach (classical theory of probability based on the axiomatic system of Kolmogorov) and the subjective, knowledge-based approach established by Cox (1946).Therefore the approach requires that aleatory variability and epistemic uncertainty can be separated and treated as independent. This is only possible if the term "aleatory variability" is applied for influencing factors outside the boundaries of the system modeled by an analyst. Therefore, the separation between epistemic uncertainty in the narrow sense and aleatory variability is model-dependent. Experience has shown that the assumption of independence is hard to achieve.

Despite the problematic character of this approach, the Ang-Tang model is the baseline uncertainty model of the SSHAC method (SSHAC, 1997). It must be mentioned that things in the SSHAC method worsened even further, because the model is not applied on a system level (treating all affecting factors outside the boundaries of a "model" system as aleatory) but even on a subsystem level. This leads to neglecting dependency between epistemic and aleatory uncertainty characteristics which are always present at the subsystem level. For example, the variability of seismic wave path characteristics is very well included in the standard regression error term of a ground motion prediction equation. This is because ground motion prediction equations are developed from large databases with recordings from different areas having different seismotectonic characteristics and different structural path characteristics. So the variability of these characteristics is already captured by the equation itself. This is also applicable to some extent for seismic source variability. This means handling seismic source and seismic path characteristics separately in a PSHA logic tree approach, without adjustment of the so-called aleatory variability of the ground motion prediction equation is leading to a systematic double counting of uncertainties. There are many other similar problems encountered in the use of the Ang-Tang model in PSHA. The use of this approach is the main reason for the large differences between ground motion predictions made by the traditional PSHA method and empirical observations. Mixing measurable empirical characteristics like the frequency of earthquakes with "lack of knowledge" characteristics like characteristics of confidence intervals of predictive equations leads to loss of information on the true characteristics of the seismic exposure and the associated risks of a region (Klügel, 2009).

To compensate for these problems, the SSHAC-procedures for treating uncertainties (SSHAC, 1997) require the broad involvement of experts in the analysis project. According to the SSHAC procedures, epistemic uncertainty is treated by presenting different modeling alternatives for the hazard parameters as different branches of a logic tree. Experts are asked to propose and evaluate different modeling alternatives, by assigning different subjective weights (probabilities) to each of the possible alternatives. These weights represent the different degree of belief of the experts in the different modeling alternatives (the weights, therefore, should sum up to 1 for each of the nodes of the logic tree). The SSHAC procedures are based on a structured expert elicitation process. The expert elicitation process is classified into four different levels of complexity (level 1 to 4 in increasing order). The process is facilitated by a TFI (Technical Facilitator and Integrator). Characteristic for this approach are the changing roles of experts involved in the process. They figure as proponents of models (usually their own) and at the same time as evaluators of proposed models (usually supported by other experts). In a level 4 study, they are regarded as the owners of the model, while at lower levels, the TFI (or even a TI (Technical Integrator)) is regarded as the owner of the model. The development of opinions is typically based on a group dynamic process attempting to achieve some consensus within the groups of experts. This type of consensus can be regarded as the minimal level of shared scientific positions and typically leads to a conservative envelope for the questions elicited. In general, experts perform differently in such expert elicitation tasks. Therefore, the SSHAC procedures place a large emphasis on the process which is essentially a group dynamic process of forming a group opinion. The SSHAC procedures allow the use of different methods for the aggregation of expert opinions, albeit that the preferred approach uses equal weights. This aggregation approach corresponds to the assumption of "infallible" experts (Klügel, 2005b), because it assumes implicitly that experts can make "bias-free" estimates. This assumption is in general not justified (Kahneman et al, 1982, Cooke, 1991). In summary it can be concluded that the SSHAC procedures are based on political consensus principles (one man one vote) or on census (extreme opinions can be rejected by the group or by assigning zero weights for lower level SSHAC approaches), rather than on principles of rational consensus, which is popular in Europe (Cooke, 1991, Cooke and Gossens 2008). It belongs to the group of behavioral expert elicitation procedures with respect to combining expert opinions (Clemen and Winkler (1999)).

The SSHAC approach is only one of many possible alternatives of using expert judgment as a source of information or a provider of scientific data. There are many alternatives on how to aggregate the results of an expert elicitation process. Many of them do not need logic trees to derive the requested probability distributions for the epistemic part of uncertainty.

In Europe, mathematical approaches to combining expert opinions are more in favor. The most popular approach for the aggregation of expert opinions into probability distributions is Cooke's "Classical Method" developed at the University of Delft. This method is based on the principles of "Rational Consensus" and implies a mathematical aggregation method resulting in performance-based weights for the different expert opinions (Cooke, 1991). The method is implemented in the software package "Excalibur" which can be obtained from its authors. Alternatively, Bayesian methods or direct aggregation methods based on the use of discrete probabilities as they are custom in financial risk assessments (Klügel 2005c, Vose, 2006) are in use as principal alternatives. It is important to mention that the results of a PSHA which is based on expert elicitation may differ significantly depending on what method for the aggregation of expert opinions was used.

5. OVERVIEW OF THE PEGASOS PROJECT (SWITZERLAND 2000-2004)

The PEGASOS project was the first European trial application of the SSHAC procedures (SSHAC, 1997) at its most elaborate level (level 4) to develop a site-specific seismic hazard for the sites of Swiss nuclear power plants (Abrahamson et al, 2004, Zuidema, 2006). The Swiss nuclear power plants sponsored the study in answer to a request from the Swiss regulator – HSK. This request was derived from discussions with a limited set of US-consultants and NRC officers. The PEGASOS project was subdivided into 4 subprojects:

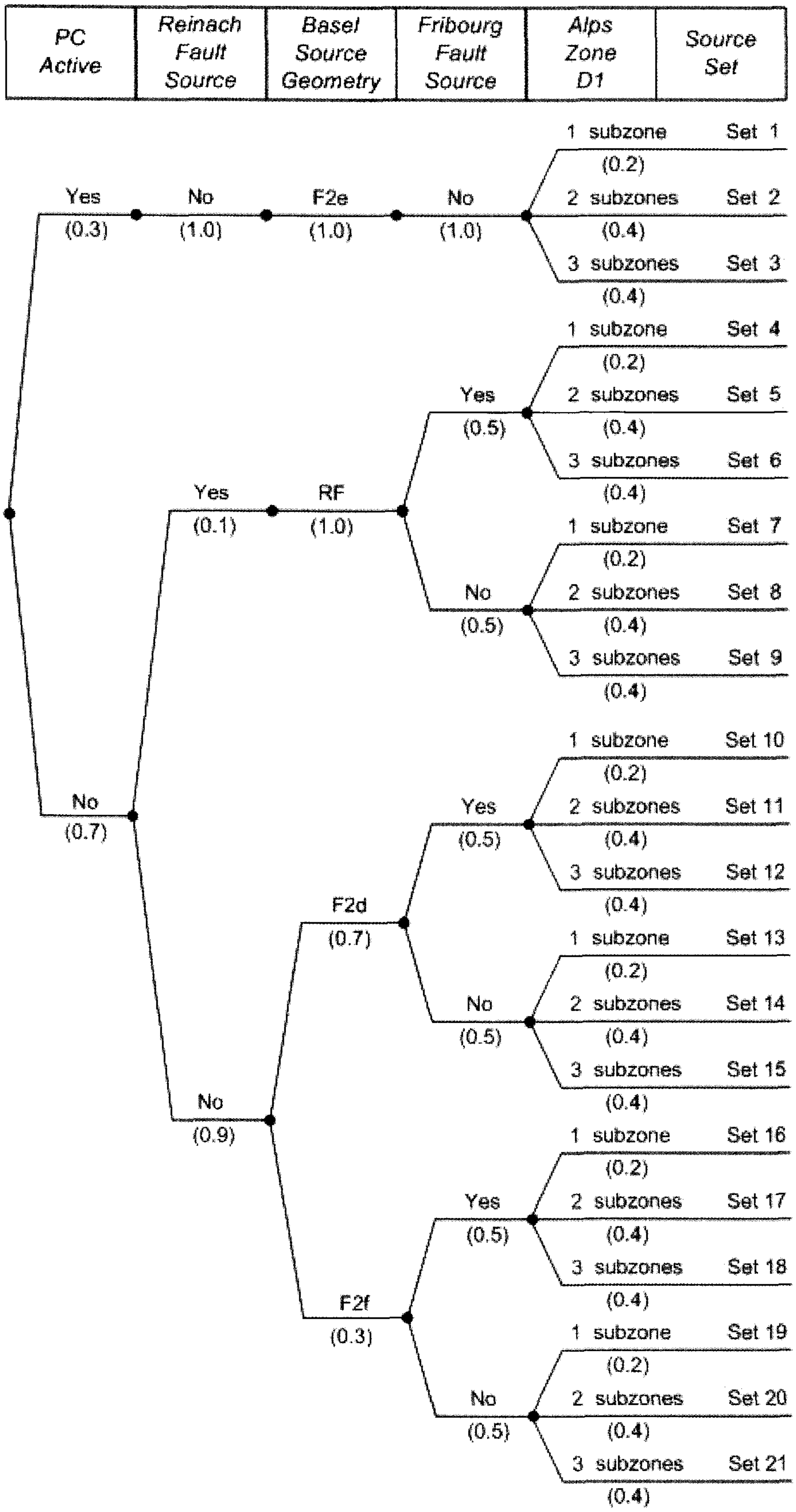

Fig. 2. Example (Partial) Logic Tree from the PEGASOS Project, Subproject 1, Expert Group E

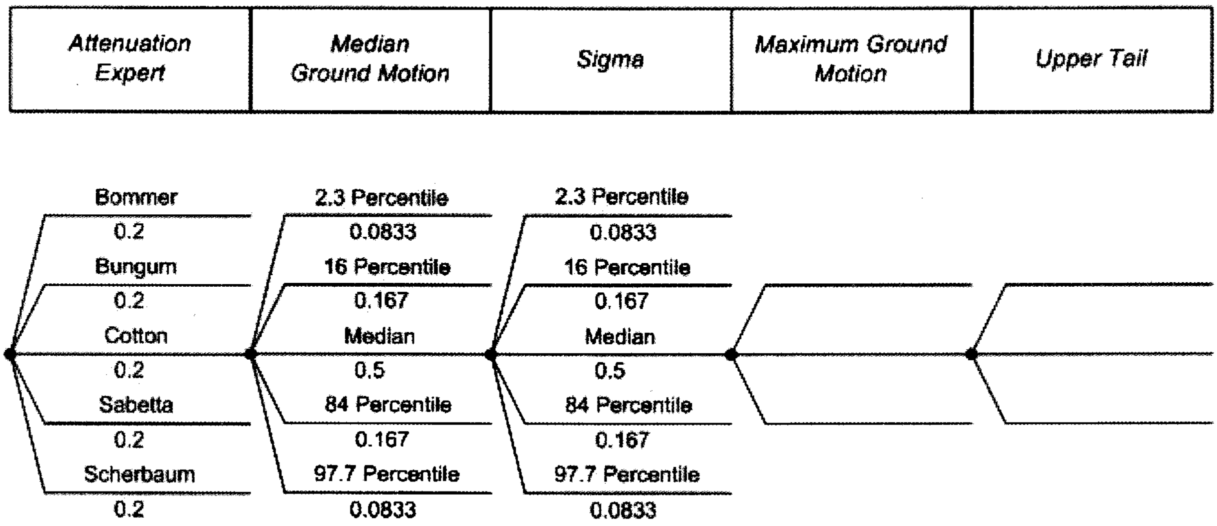

Fig. 3. Generalized Logic Tree for the PEGASOS Subproject 2 – Ground Motion Characteristics

- Subproject 1 (SP1) – Seismic source characterization – 4 groups of experts, each group consisting of three experts.
- Subproject 2 (SP2) – Ground motion characteristics – 5 experts,
- Subproject 3 (SP3) – Site response characteristics – 4 experts,
- Subproject 4 (SP4) – Hazard quantification.

Therefore, the study followed the convolution approach, separating source, ground motion and site-response characteristics. Dr. K. Coppersmith acted as the TFI (Technical Facilitator and Integrator) of subproject 1 and Dr. N. Abrahamson as the TFI for subprojects 2 and 3.

The study was based on the use of comprehensive logic trees to reflect the epistemic uncertainties related to source, ground motion attenuation and site characteristics relevant for the evaluation of seismic hazard models for the Swiss nuclear power plants. Figures 2 and 3 show examples of the logic trees used in the study (partial trees). Equal weights were used to combine the different expert opinions. Figure 3 illustrates that the Ang-Tang model of combining aleatory variability and epistemic uncertainty into a joint probability distribution was implemented on the subsystem level (σ the aleatory component is incorporated into the logic tree). An interesting feature of the project was the attempt to constrain maximum ground motion levels by an estimated upper limit. The final review of the project results by the sponsor (see Klügel 2005a, Klügel 2007) as well as by the nuclear safety authority identified the need for a further development of the probabilistic seismic hazard analysis.

Currently there is a refinement project underway (launched in 2008) which attempts to resolve some of the issues observed during the review of the first project. A new feature of the refinement project (denoted as PRP *PEGASOS Refinement Project*) is the transition to a scenario-based approach. This corresponds to step 5 in the PSHA procedure illustrated in figure 1. A new feature of the refinement project consists in the additional collection of site-specific data for soil characteristics as well as of additional geomorphological information to constrain the maximum magnitude regarded as feasible in the near field of the nuclear power plant sites. The refinement project is expected to be completed by 2011/2012.

6. IDENTIFIED ISSUES OF TRADITIONAL PSHA AND ALTERNATIVE DEVELOPMENTS

Discussing issues observed in the application of traditional PSHA methods, one has to distinguish between implementation errors as they can occur in any application of any method and generic issues associated with the methodology itself.

The most frequently observed implementation error is associated with an incorrect treatment of existing physical dependencies between modeling parameters in probabilistic models. This is associated with a lack of ability of "conditional thinking" and insufficient training in the use of subjective probabilities (Cooke, 1991). With respect to the use of the SSHAC level 4 methodology in the PEGASOS project, it was found as a deficiency of the method that none of the geoscientists involved in the development of the seismic hazard understood either the purpose of the study (realistic risk assessment) or the engineering implications of the results (Klügel 2005a;b; c).

The most important generic issues are:

1) The use of logic trees for the development of ground motion models instead of giving preference to the development of source specific or at least regional

ground motion prediction models.

2) The use of diverse ergodic assumptions applied
   a. to justify the transfer of earthquake data from one region of the world to another one
   b. to interpret the regression error term in ground motion prediction equations, which is essentially a spatial characteristic as a temporal characteristic
   c. to justify the application of De Finetti's principle of exchangeability to treat epistemic uncertainty and aleatory variability as independent in the hazard computation process (SSHAC, 1997)
3) The application of the Ang and Tang model (Ang, 1970, Ang, 1975, 1984) combining different types of uncertainty – aleatory variability and epistemic uncertainty – into a combined random parameter (Ayyub and Klir, 2006). As a side remark it is interesting to note that in the second edition of their book, Ang and Tang (Ang, 2006) dissociate themselves from this concept, emphasizing the different significances of epistemic (lack of knowledge) uncertainty and aleatory variability (randomness, e.g. variation in a population), which require that they be separately treated mathematically.
4) The preferred use of the model of a homogeneous Poisson process as the baseline stochastic process model to describe earthquake recurrence, although this has been refuted for a long period of time.
5) The extrapolation of b-values in the Gutenberg-Richter equation derived from the observation of the occurrence of small to moderate earthquakes to the range of large earthquakes.

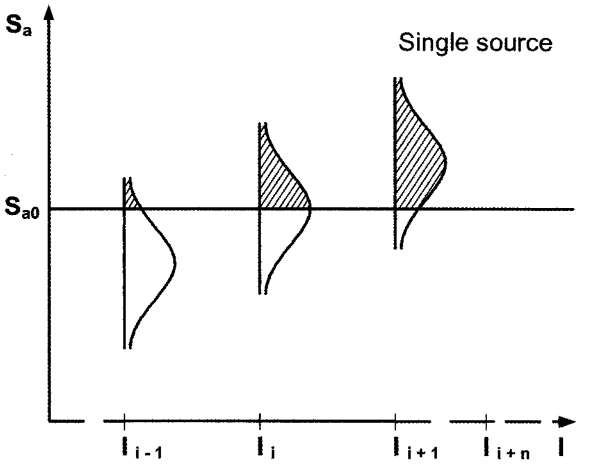

Fig. 4. Evaluation of Spectral Acceleration Exceedance in Traditional PSHA (Example for a Single Source, $I_{i-1}<I_i<\ldots I_{i+n}$)

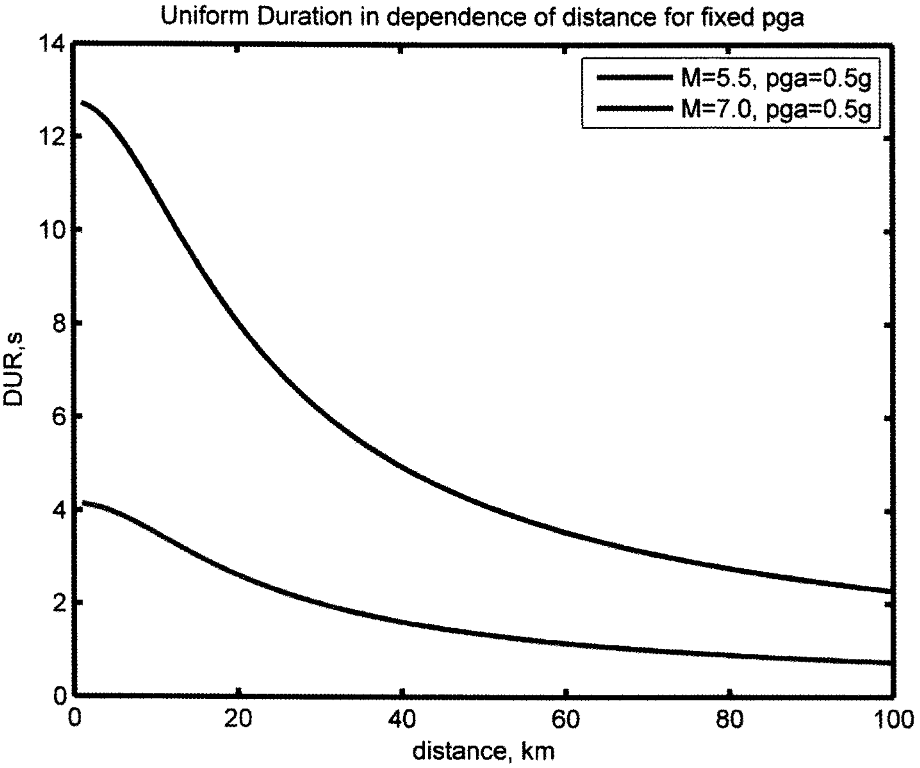

Fig. 5. Comparison of Uniform Duration of Earthquakes with Different Magnitude for Fixed Peak Geound Acceleration at the Site

6) The possible violation of energy conservation principles caused by summing up exceedance frequency contributions to a certain acceleration level from weak (low energy) earthquakes and from strong earthquakes (Klügel, 2008). This process is illustrated in figure 4. The figure shows that in the PSHA methodology, exceedance frequencies are added despite the different damaging potentials of the associated earthquakes expressed by an intensity parameter (for example EMS-98 intensity denoted as I in figure 4).
7) The belief that a uniform hazard spectrum represents a uniform hazard. This is not true. This issue is also related to figure 4. The problem is that small earthquakes may cause the same ground motion accelerations as a large one, but nevertheless cause significantly smaller damage due to their lower energy content. Combining contributions of small and large earthquakes into a unified hazard spectrum means that the hazard is not at all uniform because the contributing earthquakes have different damaging characteristics. Figure 5 compares the strong motion durations (uniform duration, see Klügel, 2008) of two earthquakes of different magnitudes (5.5 and 7 respectively) which both would result in a peak ground acceleration of 0.5 g at the site of interest (this is the result of using different levels of confidence (different values of ε in eq. (4)). Both earthquakes would be regarded as equally important contributions to a uniform hazard spectrum although their damaging potential is significantly different.
8) The use of inadequate expert opinion elicitation and aggregation methods (Klügel 2005c, Cooke, 1991, Cooke and Goossens, 2008) which are based on political consensus principles or on census principles, rather than on principles of rational consensus.

The problems identified have led to different alternate PSHA approaches which differ from the SSHAC procedures. In general these developments can be characterized as

- evolutionary developments attempting to improve traditional PSHA methods
- new developments.

Meanwhile it is widely recognized that a uniform hazard spectrum cannot be used to characterize the exposure of a site of a nuclear power plant to seismic hazard. Therefore, newer, large-scale PSHA projects like the PEGASOS refinement project (PRP) in Switzerland do not present the uniform hazard spectrum as the final result of the hazard computation. The main result of the study are the disaggregation results in terms of magnitude - distance pairs (or accompanied by additional information like focal depth and focal mechanisms) which represent the starting point for the development of realistic time-histories. Such time histories can be developed in a traditional engineering way from spectra (artificial time histories using suitable earthquake records as seeds), by using synthetic seismograms, stochastic-point-source models (Klügel et al, 2009a) or, if necessary, detailed fault source modeling techniques. This approach can be classified as the most important evolutionary development among PSHA alternatives. The main objective of these developments consists in resolving issues 6) and 7) listed above. In general it follows an idea of McGuire published in 1995 (McGuire, 1995).

Other countries (Germany and Russia) prefer to use intensities such as the hazard parameter of a PSHA (Leydecker, 2005, Klügel et al 2009b). Because intensities (especially the EMS-98 scale, Grünthal 1998) are closely linked to damage observed in earthquakes this does also support the resolution of issues 6) and 7). An interesting approach was developed by the German utilities in a joint effort of the German VGB[1]. In their approach, extreme value statistics (truncated Gumbel distributions) are used to characterize the magnitude recurrence of earthquakes for the different seismic sources, which are combined with site-intensity assignment laws (a function of magnitude, distance and site conditions) to develop site intensities. A Monte Carlo procedure is used to calculate intensity-based seismic hazard curves. The samples (magnitude –distance pairs) used in the Monte Carlo computation process are preserved and define the hazard background. This hazard background is used to develop a site-specific response spectrum using a regional ground motion prediction equation. The 50% confidence level (or "median"), at a frequency of occurrence (not exceedance) of 10^{-5}/a, is used as the basis for the design basis response spectrum. The epistemic uncertainty associated with the developed site intensity assignment law is taken into account in the Monte Carlo process (treated as aleatory variability). The German approach is a mainly data-driven effort. Geological and seismo-tectonic information is used to provide the seismic zonation used in the PSHA models.

Among the new developments, the direct scenario-based approach suggested by Klügel et al (2006) should be mentioned. This approach is mainly data-driven and also avoids the construction of a uniform hazard spectrum. It also removes some of the simplifying assumptions introduced by Cornell (1968) by separating temporal, spatial and size (magnitude) characteristics in the traditional PSHA approach. Instead of this the use of multivariate frequency distributions is suggested. To take into account the different energy content of earthquakes of different magnitude it is suggested to subdivide the magnitude range of engineering interest into a set of discrete magnitude bins. For each of the magnitude bins, the most critical scenario is developed, which provides the basis for the subsequent engineering calculations for design as well as for a probabilistic risk analysis. Because the number of scenarios is limited in depth, analysis can be performed

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[1] The author of this paper is an associated member of the corresponding VGB (Verein der Grosskesselbetreiber) working group

using all the available tools of modern neo-deterministic analysis methods (modeling seismic hazard analysis – modeling SHA, see Klügel, 2008).

7. SUMMARY AND CONCLUSIONS

The nuclear reactor oversight process in many countries has moved towards a risk-informed approach. This requires the development of complete (with respect to scope) probabilistic risk assessments (PSAs). Seismic PSA is an important part of such a PSA. A comparison of the results of different seismic PSA studies has indicated large differences which can be traced to different PSHA methods in use. A detailed review of different PSHA methods (compare Klügel, 2008) has revealed that traditional PSHA methods delivering uniform hazard spectra as the main result do not represent an adequate input as it is required for a seismic PSA. Using uniform hazard spectra based on ground motion characteristics for design may lead to overly conservative results in low-to moderate seismic areas like Europe, where? strong motion events (and subsequently recordings) are spare.

These observations are the main reasons why the intensity-based characterization of the seismic hazard is popular in some European countries. The first attempt to export SSHAC level 4 procedures to Europe (Switzerland) has not yet found broader popularity outside of Switzerland. Newer PSHA approaches, even evolutionary approaches like in the PEGASOS refinement project (PRP) are focusing on scenario-based approaches to allow for a better physical representation of the results of a PSHA study.

CONCLUDING STATEMENT

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